

Cloud formation in giant planets

Christiane Helling

*SUPA, School of Physics & Astronomy, Univ. of St Andrews, North
 Haugh, St Andrews, KY16 9SS, UK*

Abstract. We calculate the formation of dust clouds in atmospheres of giant gas-planets. The chemical structure and the evolution of the grain size distribution in the dust cloud layer is discussed based on a consistent treatment of seed formation, growth/evaporation and gravitational settling. Future developments are shortly addressed.

1. Introduction

Clouds are a common feature in gas giant and brown dwarf atmospheres, and observation start to spectroscopically infer their existence. The description of the actual formation of clouds in substellar atmospheres has been a challenge in particular if consistently calculated with radiative transfer and large-scale hydrodynamics. Various branches pressed ahead in the recent years to advanced the field of planet atmosphere modelling: i) detailed radiative transfer calculations with simplified cloud chemistry (*Fortney* and *Barman* this volume), ii) large-scale multi-dimensional hydrodynamical simulations but without dust chemistry (*Showman* and *Menou*, this volume), iii) photochemical gas-phase models for a given atmosphere stratification (*Tinetti*, this volume), and iv) detailed non-equilibrium dust-cloud modelling for a prescribed atmosphere structure. Our efforts are centred on point iv) which allows us to study details of the cloud formation process like e.g. the cloud's chemical composition and the grain size distribution function. The basic idea is that a phase-transition can only take place if the gas is supersaturated. Supersaturation requires a considerable super-cooling below the thermal stability temperature. Once seed particles have formed (nucleation), chemical surface reactions quickly form a mantle. The grain mantle consists of a variety of compounds in an oxygen-rich environment because compounds can become thermally stable in a very narrow temperature interval. The newly formed dust particles drift into deeper layers due to the high gravity of the objects and grow further on their way into warmer regions. If the temperature becomes too high, the compounds are not any more thermally stable and, hence, they evaporate. Would these processes occur in a truly static environment, no clouds would be present (*Woitke & Helling 2004*). But substellar objects possess a considerable convective over-shooting (*Ludwig et al. 2006*) which brings up uncondensed material and which keeps the circle of dust formation running. Cloud formation due to the condensation of solids/liquids reduces the remaining gas phase element abundances and their gravitational settling introduces an additional dynamic process, both changing the atmospheres appearance considerably.

In the following, we will demonstrate the results of our kinetic dust-cloud model for gas-giant atmospheres and shortly address some future developments.

2. Method

We model nucleation (seed formation), heterogeneous growth, evaporation, and drift (gravitational settling) of dirty dust particles in a quasi-static atmosphere by using the moment method (Gail& Sedlmayr 1988, Dominik et al 1993, Woitke& Helling 2004, Helling & Woitke 2006; Helling, Woitke & Thi 2007). We consider the formation of compact spherical grains in an oxygen-rich gas by the initial nucleation of TiO_2 seed particles, followed by the growth of a dirty mantle. The moment and elemental conservation equations are evaluated for given $(T, \rho, v_{\text{conv}})$ either for a prescribed static model atmosphere structure or inside a iterative solution of the radiative transfer problem. Our dust model calculates the amount of condensates, the mean grain size $\langle a \rangle$, the parameterised grain size distribution function, and the volume fractions V_s of each material as a function of height z in the atmosphere. 12 solids made of 8 elements are considered to form the grain mantle by 60 chemical surface reactions. We solve 19 stiff differential equations already in the dust and element conservation complex.

3. Results

3.1. Dust composition in atmospheres of gas-giant planets

Figure 1 (top) shows the cloud’s material composition for a gas giant. The upper cloud regions are populated by small silicate grains which are composed mainly of $\text{Mg}_2\text{SiO}_4/\text{MgSiO}_3$ and SiO/SiO_2 . Iron-binding solids are thermally stable and contribute in total as much as the Mg-binding compounds do. Two instability regions occur where the cloud’s material composition changes considerably: One is where the iron compounds and SiO evaporate, and a second one occurs at higher temperatures where all the remaining silicates evaporate. We note a stratified purification of the dust cloud. The warmest dust cloud layers are mainly made of Fe[s] and $\text{Al}_2\text{O}_3[\text{s}]$ with little inclusions of $\text{TiO}_2[\text{s}]$ and $\text{CaTiO}_3[\text{s}]$. Grains forming the cloud base have large mean grain sizes and the grain size distribution $f(a)$ is very narrow. Figure 1 (bottom) shows that $f(a)$ is δ -function-like at the very right of the plot (i.e. large grain size a) relating to the cloud base.

3.2. Grain size distributions in atmospheres of gas-giant planets

The grain size distribution $f(a)$ is based on the solution of our moment equations and is here parameterised as a potential exponential size distribution. Figure 1 (bottom) demonstrates that the size distribution changes with height in the atmosphere. The l.h.s. of the plot (blueish) shows the nucleation regime and $f(a)$ is δ -function-like also at the cloud deck. It broadens and increases if nucleation and growth run in parallel. If nucleation ceases, $f(a)$ moves through the grain size space towards larger grains until evaporation sets in. Evaporation causes the smallest grains to disappear, hence, $f(a)$ decreases and narrows. Evaporation

also decreases the size of existing grains, hence, $f(a)$ broadens considerably towards smaller grain sizes. We have, hence, shown that it is difficult to attribute a single grain size to a cloud and that the shape of the grain size distribution varies through the entire cloud.

4. The future

Detailed micro-physical models of cloud formation allow the study of the actual formation and evolution of the atmospheric cloud constituents. It is, however, deemed challenging to couple a complete micro-physical model consistently with atmosphere simulations and still preserve its flexibility. Additionally, the coupling of dust *formation* and multi-dimensional hydro-simulations needs to deal with the time-scale problem between chemistry and fluid dynamics, and with the turbulent closure problem. However, Dehn et al. (2007) did combine a reduced version of our kinetic cloud formation model with the 1D PHOENIX model atmosphere code by Hauschildt & Baron (1999) and first consistent simulations become available.

Generally, the solution of the stellar/planetary atmosphere problem should be determined by only the stellar/planetary parameter and ideally, no parameter would be attributed to clouds, day-night-effects etc. The hope is that the solution of the atmosphere problem (classically: hydrostatic equilibrium, radiative transfer, mixing length theory, gas-phase chemical equilibrium + cloud model) is unique, and hence, the resulting synthetic spectrum is determined by this stellar/planetary parameter combination, too. It is, however, noticeable difficult to identify a single stellar/planetary parameter combination that fits an observed spectral range (e.g. Brandecker et al. 2006). To advance this situation, modellers have set out to conduct a comparative study of cloud models in order to provide a measure for uncertainties inherent to substellar model atmospheres¹.

References

- Ackerman A.S., Marley M.S. 2001, ApJ, 556, 872
 Brandecker A., Jayawardhana R., Ivanov V.D., Kurtev R. ApJL, 653, 61
 Dehn M., Helling Ch., Woitke P., Hauschildt P.H. 2007, ApJL, submitted
 Dominik C., Sedlmayr E., Gail H.-P. 1993, A&A, 277, 578
 Gail H.-P., Sedlmayr E. 1988, A&A206, 153
 Hauschild P., Baron E. 1999, JCAM 109, 41
 Helling, Ch. & Woitke, P. 2006, A&A, 455, 325
 Helling, Ch. & Woitke, P. 2007, A&A, submitted
 Ludwig H.-G., Allard F., Hauschildt P.H. 2006, A&A, 459, 599
 Woitke, P. & Helling, Ch. 2004, 414, 335
 Woitke, P. & Helling, Ch. 2003, 399, 297

¹<http://www.lorentzcenter.nl/lc/web/2006/203/info.php?wsid=203>

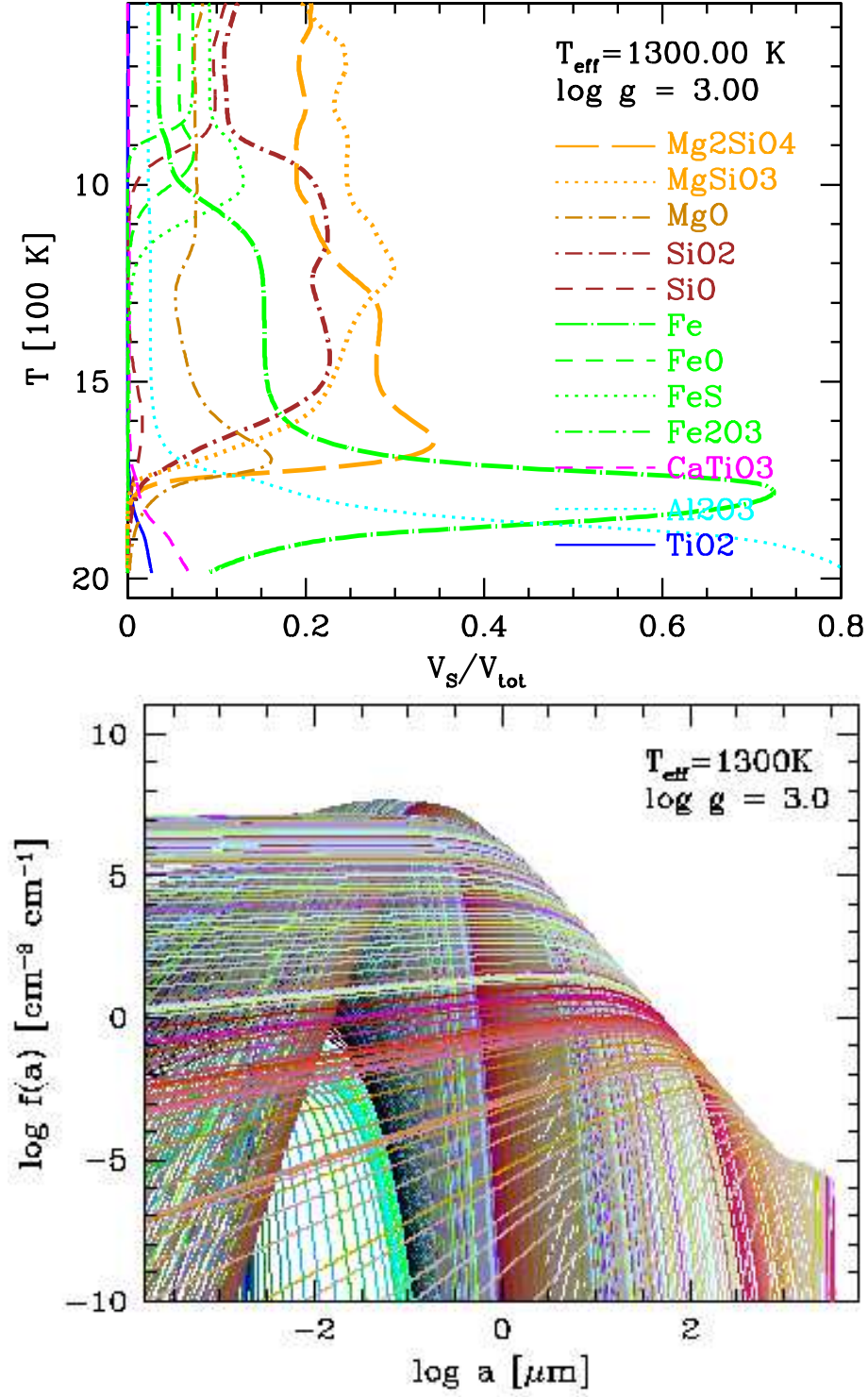


Figure 1. Atmospheric dust cloud in a giant gas-planet with $T_{\text{eff}} = 1300 \text{ K}$, $\log g = 3.0$. **Top:** Material composition (in volume fractions) of the dust cloud. **Bottom:** Grain size distribution functions for each atmospheric layer in the dust cloud.